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THERMAL RADIATION FROM HIGH-TEMPERATURE AIR

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FOR THE COMMANDER:
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The work reported herein represents part of a thesis submitted to the faculty of the Graduate School of the University of Maryland in partial fulfillment of requirements for the degree of Master of Science

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ABSTRACT

Thermal flux radiated from an isothermal slab of air is calculated, assuming one-dimensional radiation flow for a wide range of gas temperatures and densities and using the latest absorption coefficient data available.

The effects of assuming an optically thin gas and different absorption coefficient data are considered. Criteria for specifying air as optically thin or optically thick are included. The energy lost from the system by radiation is compared with the total energy of the system.

1. INTRODUCTION

Radiant heat transfer can be an important and, in some cases, the predominant means of heating a missile or satellite in flight (ref 1). Realization of this effect has led to fundamental studies of the radiative properties of the various species comprising air (ref 2, 3). Use of the knowledge obtained from these studies, however, is restricted by the complicated nature of the physical situation and the resulting mathematical expressions. Many simplifying assumptions are required before a calculation can be made.

This report includes calculations of the energy radiated by air over a wide range of temperatures and densities. The derivation of the equation used in the calculation is outlined explicitly, giving the assumptions involved. The effects of using different assumptions are shown. Thus, the final result is not only a set of data based on the most recent information but also allows an estimate of the data's validity within the assumptions made.

2. RADIANT ENERGY TRANSFER PROPERTIES

2.1 Calculation of Thermal Radiant Energy

The radiation emitted by high-temperature air is calculated, starting from fundamental principles that are used with the most recent data available on the emissive properties of air. The independent variable is the temperature with density ratio as a parameter. This arrangement allows direct entry into tables of shock-wave properties, such as those calculated in references 3 and 4.

The radiant flux emitted by a volume of high-temperature gas is determined by the balance of emission and absorption processes occurring within the gas. In this report scattering processes are assumed to be negligible. Using the appropriate expressions defined in appendix A, the radiative energy change in a volume of radiating gas is found to be

$$\frac{dI_\nu}{ds} = \left(j_\nu - I_\nu K_\nu\right) \rho \tag{1}$$

(The symbols used in this report are explained in appx A.) I_ν and j_ν are dependent upon the direction of the radiation flow. Assuming local thermodynamic equilibrium, we can write for the steady-state case

$$\frac{1}{\rho K'_\nu} \frac{dI_\nu}{ds} = B_\nu - I_\nu \tag{2}$$

where the effects of induced emission have been taken into account by introducing

$$K'_\nu = K_\nu \left[1 - \exp\left(-\frac{h\nu}{kT}\right)\right] \tag{3}$$

Goulard (ref 5) and Pai (ref 6) have solved equation (2) for a one-dimensional case. Using spherical coordinates, the intensity is then independent of the azimuth angle φ but dependent on the altitude angle θ. Using their results (ref 5, 6), together with the assumptions of an isothermal slab of a gray gas (K_ν independent of ν) with no interacting solid surfaces, we find for the emitted flux:

$$Q = \sigma T^4 \left[1 - 2\, E_3(t)\right] \tag{4}$$

where t is the integrated optical path.

The Planck mean absorption coefficient K_p is used in this report. It is the mass absorption coefficient K_ν weighted with respect to the Planck emissive function. (Appendix A defines K_p in detail.) The Planck coefficient is independent of ν and fulfills the requirement of a gray gas. K_p is exact only for an optically thin gas. The mass absorption coefficients for air in equilibrium have been calculated by Meyerott, et al (ref 7), using quantum theoretical and experimental techniques. The work of Gilmore (ref 8) was used by Meyerott as the basis for determining the constituents of air. Gilmore's constituent results do not differ appreciably from those of Hilsenrath (ref 9, 10), which were used in the shock-wave calculations of references 3 and 4.

Armstrong (ref 11), using the work of Meyerott (ref 7), calculated K_p as a function of density and temperature. For use in this report, Armstrong's tabular results have been carefully plotted in figure 1 to give a continuous set of values.

The function $E_3(t)$ appearing in equation (4) was calculated by Case (ref 12). For use in this report, Case's data were fitted to the curve

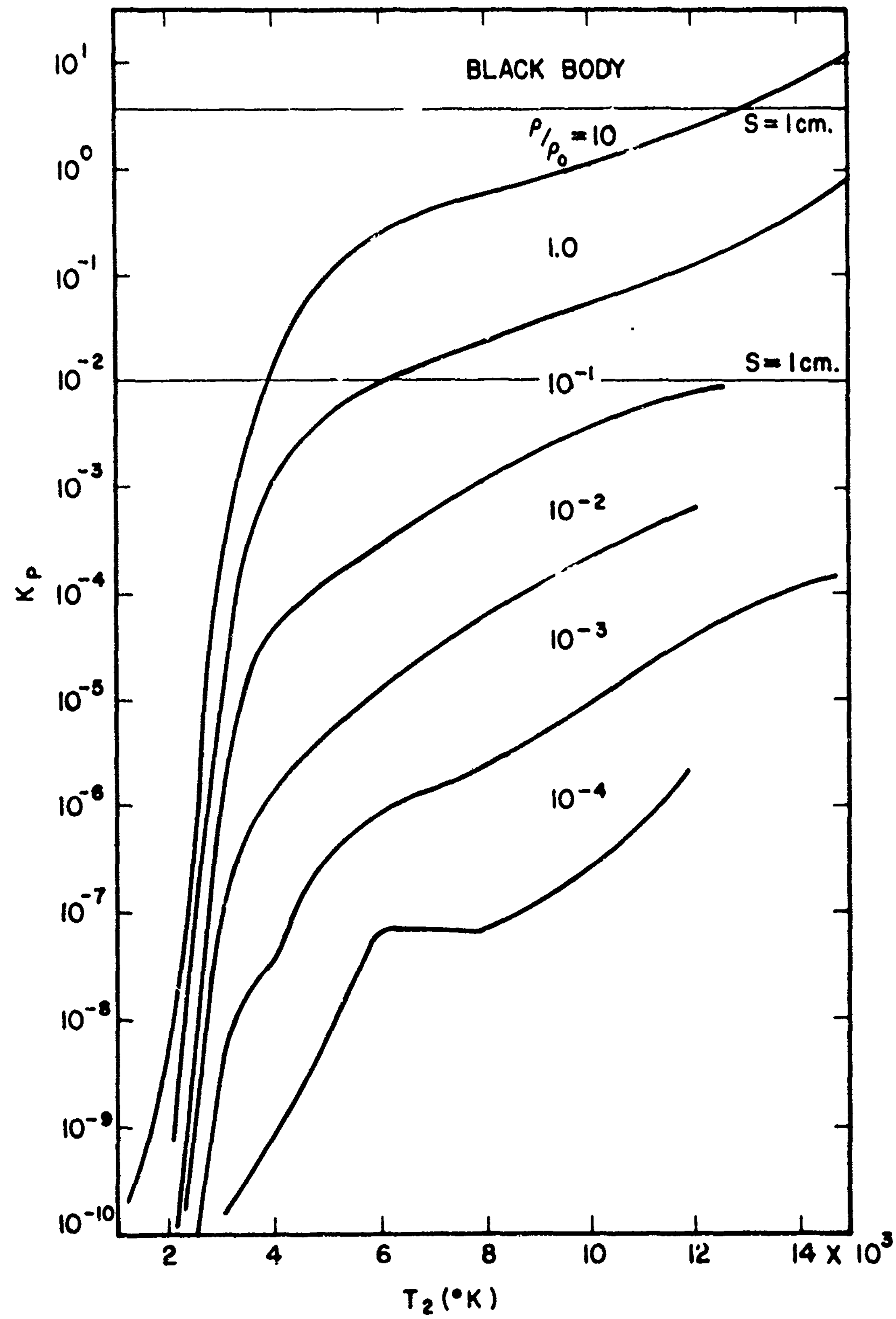

Figure 1. Planck mean absorption coefficients.

$$E_3(t) = a + bt + ct^2 + dt^3 + et^4 \tag{5}$$

Over a range of $0.0 \leq t \leq 3.4$, the coefficients were found to be

$$a = 5.000000$$
$$b = -0.765638$$
$$c = -0.501736$$
$$d = -0.151243$$
$$e = 0.016886$$

The result of this fit is shown in figure 2 where $[1-2E_3(t)]$ is plotted against t for the original and fitted data.

The radiation from air over a range of 3000° to 12,000° K and densities from 10^{-3} to 10 times atmospheric were calculated, using the mean absorption coefficients of Armstrong (ref 11) and equation (4). All calculations were programed by the author for the IBM 7090 computer. The results are shown in figure 3 for a path length of 1 cm. It can be seen that the radiation emitted from hot air can be appreciable, even at the lower densities.

2.2 Comparison of Calculated Data

The enthalpy H, which must flow into a gaseous system to reach its high-energy state, can be calculated from

$$H = \rho U_s H' \tag{6}$$

This quantity was calculated, using the density and shock velocity found in reference 4, and the enthalpy per unit mass of reference 10. The results are given in figure 3, where 1 percent of the inflowing enthalpy is shown. It can be seen that over the range considered, the radiated energy is a small fraction of the total energy of the system. Corrections to the thermodynamic properties for the radiated energy would be small.

Figure 3 also gives the energy emitted by a black body over the temperature range considered. It can be seen that the emitted energy approaches this limit at the higher densities and temperatures. K_p is exact for an optically thin case, but its use is questionable in the high-density and high-temperature regions. An estimate of how much error results from the use of the radiation curve based on K_p can be made by examining the work of Strack (ref 13), who evaluates the integral

$$Q = \pi \int_0^\infty B_\nu \, [1-2E_3(\rho K_\nu s)] \, d\nu \tag{7}$$

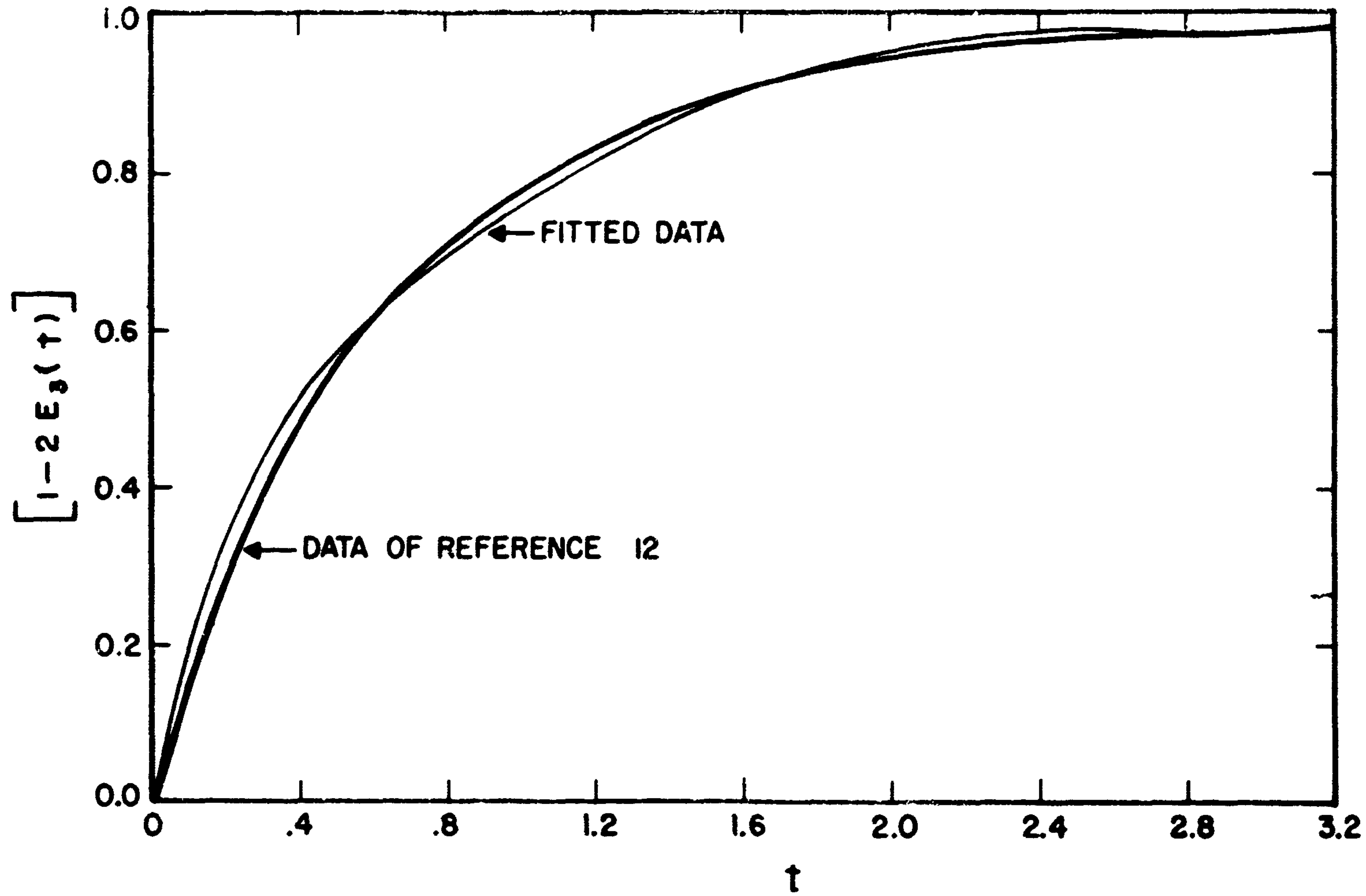

Figure 2. Comparison of fitted and original $E_3(t)$ function.

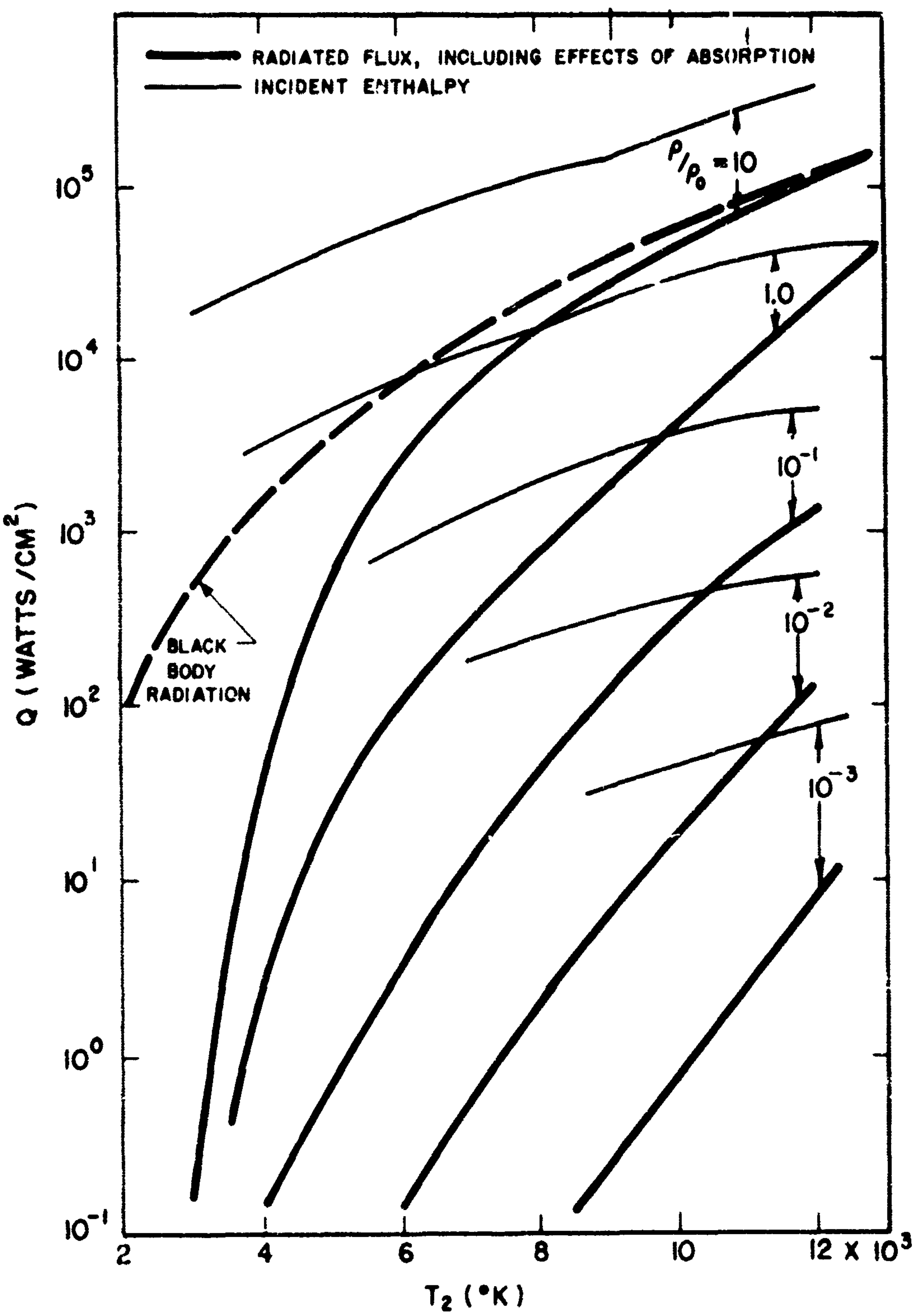

Figure 3. Radiated flux and 1 percent of incident enthalpy.

using the data of reference 7. Strack finds that his results differ by 60 percent from those obtained using K_p in the region

$$10^{-3} \leq K_p s \leq 10 \tag{8}$$

Strack's results are compared with the calculations made in this report (fig. 4) for densities of 10 1, and 10^{-2} times atmospheric. There is no difference in the radiation emitted at the lowest density, but differences up to 25 percent are noted at the higher densities in the cases considered.

Strack's results are effective criteria for the ranges of optically thin or optically thick air. This can be seen by considering figure 2. For $t \geq 3.5$, the quantity $[1-2E_3(t)] \approx 0.99$. Since the function approaches 1.0 asymptotically, those gases emitting 99 percent of the black-body value may be considered as black bodies.

The optically thin gas limit can be obtained from equation (4), using the expansion found in reference 14:

$$E_3(t) = \frac{1}{2} - t - f(t)^2 \tag{9}$$

which, for $t \ll 1$, yields

$$Q = 2t\sigma T^4 \tag{10}$$

The limits obtained above, namely:

$$10^{-2} \geq K_p s \geq 3.5 \tag{11}$$

disagree with those of Strack's limits, but they do indicate that the differences he finds are in the region where the gas is neither optically thin nor optically thick.

The criteria for optically thin or optically thick gases, expressed by the inequality given in equation (11), are applied to the calculation made in this report by the horizontal lines shown in figure 1.

The effect of absorption can be seen by comparing the calculations already made with the optically thin case as given by equation (10). Armstrong's K_p's (ref 11) were used in equation (10) and the results shown in figure 4. The amount of radiation is the same for the two cases at the lowest density. At the other densities, it can be seen that the decrease in emitted flux caused by absorption is about 10 percent at the lower temperatures. The flux emitted by the optically thin gas will not "cut off" at the black-body limit as

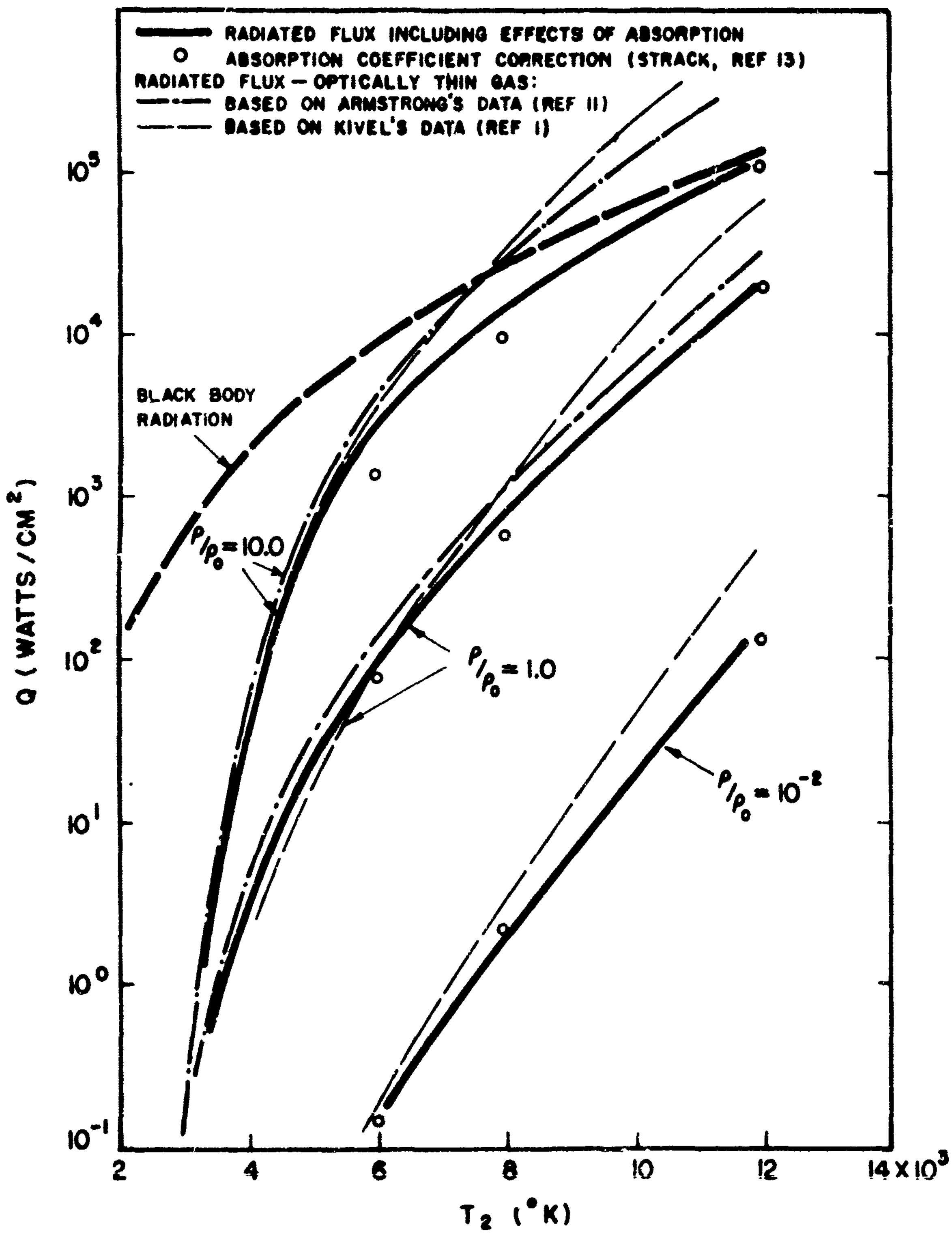

Figure 4. Comparison of radiated fluxes.

temperature is increased. This point is specifically made in figure 4 by the curve representing radiation from optically thin gas at the highest density.

The radiant flux from an optically thin gas has been calculated by Kivel (ref 1), who uses his own calculation (ref 15) for the emissive properties of air. His results are compared with the optically thin calculation made in this report in figure 4. The lack of agreement shown is chiefly due to the choice of different emissive properties of air for each calculation.

3. SUMMARY AND CONCLUSIONS

All the calculations made in this report assume an isothermal slab of gas that is in a state of local thermodynamic equilibrium. It is further assumed that no solid surfaces are interacting with the radiating gas and that the radiation flow is one-dimensional.

Within the limits imposed by these assumptions, equation (4) is the most general expression used. This equation is used to calculate the radiation from a slab of air 1.0 cm thick over a wide range of temperatures and densities (fig. 3). Radiation from slabs of different thickness may be calculated using the data of figure 2.

The results of using equation (4) with K_p are not completely accurate because K_p is exact only in optically thin gases. Corrections may be introduced by using data derived from equation (7). These corrections range up to 60 percent of the total radiation but apply only over limited ranges of temperature and density. A conservative estimate of the regions where these corrections apply is given by the inequality expressed in equation (8). This inequality, together with the data of figure 1, can also be used to define regions where air is optically thin or optically thick.

The enthalpy represented by the escaping radiation is compared with the total enthalpy of the system (fig. 3). Within the temperature range considered, the escaping radiation has little effect or the energy state of the system.

The assumption of an optically thin gas is often made. Equation (10) is the result of this assumption. This result is compared with the case of appreciable self-absorption as represented by equation (4) in figure 4. A difference of approximately 10-percent exists between the two cases at lower temperatures. The optically thin expression does not "cut off" at the black-body limit, so the divergence between the two cases steadily increases as temperature increases.

Although the absorption coefficient used is based on the most recent data available (ref 11), a comparison with older but accepted data (ref 1) indicates that more research is needed on the fundamental properties of air.

4. REFERENCES

(1) Kivel, B., "Radiation from Hot Air and Stagnation Heating," AVCO Research Laboratory, Research Report 79, 1959.

(2) Meyerott, R., "Radiation Heat Transfer to Hypersonic Vehicles," Third AGARD Combustion and Propulsion Panel Colloquium Palermo, Sicily; 1958.

(3) Hochstim, A., "Gas Properties Behind Shocks at Hypersonic Velocities," Convair Physics Group Report Zph - 002, 1957.

(4) Davis, H., "Equilibrium Thermodynamic Properties Existing Behind Shock Waves in Air, Nitrogen and Oxygen," (in preparation).

(5) Goulard, R. and K., "One-Dimensional Heat Transfer in Radiant Media," Int. J. Heat Mass Transfer 1, 81, 1960.

(6) Pai, S. I., "Some Considerations on Radiation Magnetogasdynamics," paper in "Nonlinear Problems", The University of Wisconsin Press, Madison, Wisconsin, 1963.

(7) Meyerott, R., Sokoloff, J. and Nicholls, R., "Absorption Coefficients of Air," Air Force Cambridge Research Center, Geophysics Research Paper 68, 1960.

(8) Gilmore, F., "Equilibrium Composition and Thermodynamic Properties of Air to 24,000° K," Rand Corp Report RM 1543, 1955.

(9) Hilsenrath, J., Klein, M., and Wooley, H., "Tables of Thermodynamic Properties of Air Including Dissociation and Ionization from 1500°K to 15,000°K," Arnold Engineering Development Center Report AEDC-TR-59-20, 1959.

(10) Hilsenrath, J. and Klein, M., "Tables of Thermodynamic Properties of Air in Chemical Equilibrium Including Second Virial Corrections from 1500°K to 15,000°K," Arnold Engineering Development Center Report AEDC-TDR-63-161, 1963.

(11) Armstrong, B., et al, "Radiative Properties of High Temperature Air," J. Quant. Spectros. Radiat. Transfer 1, 143, 1961.

(12) Case, K., et al, "Introduction to the Theory of Newton Diffusion, Vol I, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, 1953.

(13) Strack, S., "Hot Gas Radiation Calculations," A.R.S. Journal 32, 1404, 1962.

(14) Kourganoff, V., "Basic Methods in Transfer Problems," Oxford at the Clarendon Press, London, 1952.

(15) Kivel, B. and Bailey, K., "Tables of Radiation from High Temperature Air," AVCO Research Laboratory, Research Report 21, 1957.

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APPENDIX A. NOMENCLATURE AND DEFINITIONS USED IN CALCULATION OF RADIANT ENERGY TRANSFER

Planck's Function, B_ν

$$B_\nu = (2h/c^2)\ \nu^3 \left[\exp\left(\frac{h\nu}{kT}\right) - 1\right]^{-1} \tag{A-1}$$

equals the energy radiated from a point in a black body in a given direction per unit solid angle per unit time per unit projected area of the emitter.

- c = velocity of light,
- h = Planck's constant,
- k = Boltzmann's constant,
- T = absolute temperature, and
- ν = frequency of emitted radiation; using ν as a subscript denotes a frequency dependent quantity.

$$B = \sigma T^4 \tag{A-2}$$

equals energy radi·ted from a point in a black body at all frequencies into a solid angle of 2π per unit time per unit projected area of the emitter. σ is the Stefan-Boltzmann constant.

$$E_3(t) = \int_1^{\infty} u^{-3}\ [\exp\ (-tu)]du$$

$$u = \sec\ \theta \tag{A-3}$$

Specific Intensity, I_ν

$$I_\nu \equiv \lim_{(d\sigma,\ d\omega,\ dt,\ d\nu \to 0)} \frac{dE_\nu}{d\sigma\ \cos\ \theta\ d\omega\ dt\ d\nu} \tag{A-4}$$

dE_ν = total amount of energy passing through the element of area $d\sigma$ inside the element of solid angle $d\omega$ in time interval dt and in the frequency interval $(\nu,\ \nu + d\nu)$.

θ = angle between the normal to the emitter's surface and the given direction.

Mass (or Monochromatic) Absorption Coefficient, K_ν

$$dI_{\nu,ab} \equiv -K_\nu \rho\ I_\nu\ ds \tag{A-5}$$

$dI_{\nu,ab}$ = radiative intensity absorbed in gas

ds = element of path length over which radiation travels.

ρ = gas density.

Mass Absorption Coefficient Considering Induced Emission, K_ν'

$$K_\nu' = K_\nu \left[1 - \exp\left(-\frac{h\nu}{kT}\right)\right] \tag{A-6}$$

Emission Coefficient, j_ν

$$dE_{\nu,\ell m} \equiv j_\nu \, dm \, d\omega \, dt \tag{A-7}$$

$dE_{\nu,\ell m}$ = energy emitted from an element of mass dm into the element solid angle $d\omega$ in time interval dt and in the frequency interval $(\nu, \nu + d\nu)$.

j_ν = $K_\nu B_\nu$ (gas in thermodynamic equilibrium)

Planck Mean Absorption Coefficient, K_p

$$K_p = \frac{\pi\rho \int_0^\infty K_\nu' B_\nu \, d\nu}{\sigma T^4} \tag{A-8}$$

Flux of Radiation, Q

$$Q = \int_\omega \int_0^\infty I_\nu d\nu \cos\theta \, d\omega \tag{A-9}$$

equals net flux of radiation per unit area per unit time

$$Q_\nu \equiv \epsilon_\nu B_\nu \tag{A-10}$$

ϵ_ν = emissivity

Optical path, t

$$t = \int_0^\infty \int_0^s K_\nu' \rho \, ds \, d\nu \tag{A-11}$$

Gas Properties

H = enthalpy flux

H' = enthalpy per unit mass of gas

U_g = velocity of gas

ρ = gas density

ρ_0 = gas density at 1-atm pressure